Chapter 4
Reservoirs

4-1. Overview

This chapter presents special requirements for formulating and evaluating flood damage reduction measures obtained by reservoirs. Reservoirs reduce damage by reducing discharge directly. Table 4-1 is a checklist that summarizes critical requirements for reservoirs.

4-2. Applicability

A reservoir is well-suited for damage reduction in the following cases:

a. Damageable property is spread over a large geographic area with several remote damage centers and relatively small local inflow areas between them.

b. A high degree of protection, with little residual damage, is desired.

Table 4-1
Checklist for Reservoirs

Hydrologic Engineering Study Components	✓	Issues
Layout		Consider alternative sites based on drainage area versus capacity considerations
		Delineate environmentally sensitive aquatic and riparian habitat
		Identify damage centers, delineate developed areas, define land uses for site selection
		Determine opportunities for system synergism due to location
Economics		Determine with-project modifications to downstream frequency function for existing and future conditions
		Quantify uncertainty in frequency function
		Formulate and evaluate range of outlet configurations for various capacities using risk-based analysis procedures
Performance		Determine expected annual exceedance probability
		Determine expected lifetime exceedance probability
		Describe operation for range of events and analyze sensitivity of critical assumptions
		Describe consequences of capacity exceedances
		Determine event performance
		Conduct dam-safety evaluation
		Formulate OMRR&R plan and prepare O&M manual to include surveillance and flood fighting
Design		Formulate/evaluate preliminary spillway/outlet configurations
		Conduct pool sedimentation analysis
		Evaluate all downstream hydrologic and hydraulic impacts
		Formulate preliminary operation plans
Environmental and Social		Evaluate with-project riparian habitat
		Evaluate aquatic and riparian habitat impact and identify enhancement opportunities
		Anticipate and identify incidental recreation opportunities

c. A variety of property, including infrastructure, structures, contents, and agricultural property, is to be protected.

d. Water impounded may be used for other purposes, including water supply, hydropower, and recreation.

e. Sufficient real estate is available for location of the reservoir at reasonable economic, environmental, and social costs.

f. The economic value of damageable property protected will justify the cost of constructing the reservoir.

4-3. Reservoir Operation Overview

a. Figure 4-1 illustrates a multiple-purpose reservoir. A reservoir reduces flood inundation damage by temporarily holding excess runoff then releasing that water downstream to the channel, either through the normal outlet system or over the emergency spillway for rare events, at a lesser rate over a longer period of time. This permits a reduction in peak flow rate, resulting in lower stage and less damage. The rate of release depends on the characteristics of the outlet works and spillway. Note that in the illustration, the outlet serves two purposes: It limits the release of water during a flood event, and it provides a method of emptying the reservoir flood control pool after the events.

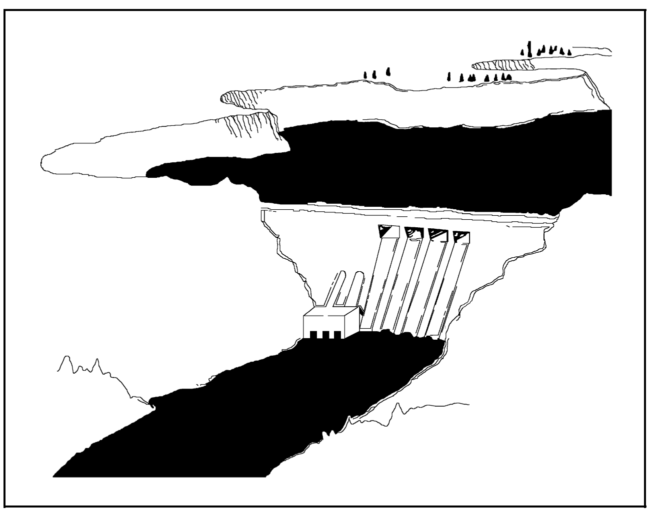

Figure 4-1. Multipurpose flood control reservoir

b. Detention storage systems are simpler flood storage systems normally implemented in urban settings as shown in Figure 4-2. They function in a manner similar

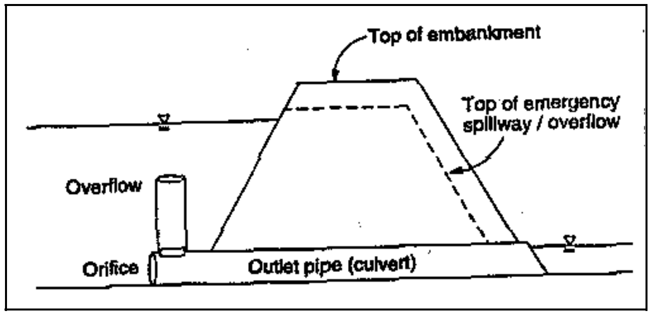

Figure 4-2. Simple detention storage facility

to that of major reservoirs by modifying flood releases downstream of the project. The releases are typically uncontrolled such as shown in Figure 4-3. In this figure, the existing-condition, without-project peak discharge from a small catchment is 186 m^3/sec. This rate exceeds the maximum nondamaging discharge for the downstream reach, 113 m^3/sec, which is denoted “target flow” in the figure. To reduce the damage, storage is provided. The volume of water represented by the shaded area in the figure is held and released gradually at a rate that does not exceed the target. The total volume of the inflow and outflow hydrographs is the same, but the time distribution is altered by the storage.

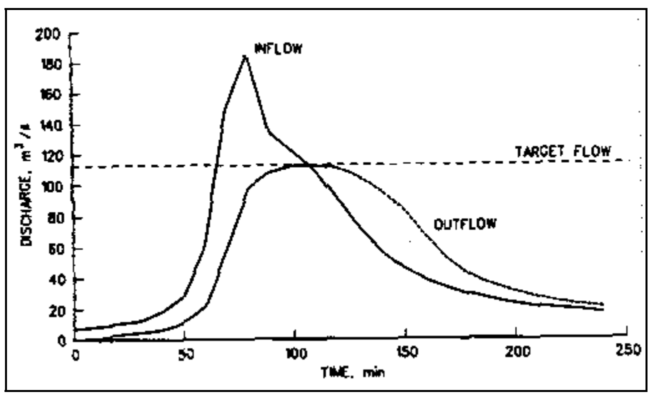

Figure 4-3. Impact of storage

4-4. Discharge-Reduction Assessment

a. The primary effect of storage is reduction of discharge, and this is modeled for individual runoff events with the routing models described in EM 1110-2-1417. Outflow from an impoundment that has horizontal water surface can be computed with the so-called level-pool routing model (also known as modified Puls routing model). A number of computer programs described in Appendix B include this reservoir routing model. The reduction in discharge peak for individual events will translate, over the long term, into modification in the discharge-frequency function. This, in turn, yields a reduction in expected damage. The modified discharge-frequency function can be found by either:

(1) Evaluating reservoir operation with a long series of historical inflows and estimating regulated discharge probability from frequency of exceedance of magnitudes of the simulated reservoir outflow series, or

(2) Evaluating operation for a limited number of historical or hypothetical events. In this case, the probability of the unregulated inflow peak commonly is assigned to the peak of the corresponding computed outflow hydrograph. This is repeated for a range of runoff events to define adequately the modified discharge-frequency function. Hypothetical runoff events may be developed from rainfall-runoff analysis with rain depths of known probability, or from discharge duration-frequency analysis. In the first case, storms of specified probability are developed and the corresponding runoff hydrographs are computed with procedures described in EM 1110-2-1417. The runoff hydrographs are inflow to the reservoir. The peak outflows commonly are assigned probabilities equal to the corresponding storm probabilities. In the second case, a balanced inflow hydrograph is developed. This balanced hydrograph has volumes for specified durations consistent with established volume-duration-frequency relations. For example, a 0.10-probability balanced hydrograph is developed so the peak one-hour volume equals the volume with probability 0.10 found through statistical analysis of runoff volumes. Likewise, the hydrograph's 24-hour volume equals the volume with probability 0.10. With either of the hypothetical inflow events, reservoir operation is simulated and the outflow peak is assigned the same probability as the inflow hydrograph. This is repeated for a range of hypothetical rainfall events to define adequately the modified discharge-frequency function.

b. Figure 4-4 shows typical modifications to the discharge-frequency function due to a reservoir. In this figure, the solid line represents the inflow and the without-project outflow discharge-frequency function. (Note that the straight line shown here and in subsequent figures is a simplification for illustration. Discharge-frequency functions are not always straight lines when plotted on normal probability paper. See EM 1110-2-1415 for further explanation.) Q_1 represents a target flow; this may be the channel capacity downstream, the flow corresponding to the maximum stage before damage is incurred, or any other target selected for a particular floodplain. Ideally, a reservoir would be designed and operated to maintain releases less than or equal to this target. If the inflow peak is less than the target, the reservoir need not exercise any control. If the inflow peak exceeds the target, the reservoir should restrict outflow to the target rate. Consequently, the with-project frequency function, which is shown as a dashed line, is equal to the without-project frequency function for events of exceedance probability greater than P_1 (events with discharge less than Q_1). For inflow events of exceedance probability less than P_1, release is limited to Q_1. However, regardless of the reservoir capacity, some extreme inflow events with peaks greater than Q_2 and probabilities less than P_2 will exceed the capability of the reservoir to limit the outflow to Q_1. The reservoir may reduce flow somewhat, but as the magnitude of the events increases (and the probability decreases), the regulated outflow peaks will approach the inflow peaks. The reservoir will have less and less impact. Finally, for an event with inflow peak equal to Q_3, the reservoir will have negligible impact, and the without-project and with-project frequency function will be identical.

4-5. Performance Considerations

The performance of a reservoir depends on its capacity, configuration, and location and on its operation rules.

a. Capacity, configuration, and location. Table 4-2 suggests steps for evaluating reservoir alternatives. Additional guidance is available in EM 1110-2-1602, in EM 1110-2-1603, from the Bureau of Reclamation (1977), and from ASCE/WEF (1992).

b. Operation rules.

(1) For a simple uncontrolled reservoir, discharge reduction, and hence damage reduction, depends on the hydraulic characteristics of the structure. The computations for these systems can be done with a specialized computer program, such as HEC-1. For a reservoir with gates and valves that can be controlled, the damage reduction depends also on operation rules. Operation rules specify how and when the gates and valves are to be opened. Typically, flood-control operation rules define the release to be made in the current time period as a function of one or more of the following: current storage in the reservoir, forecasted inflow to the reservoir, current and forecasted downstream flow, and current storage in and forecasted inflow to other reservoirs in a multiple reservoir system.

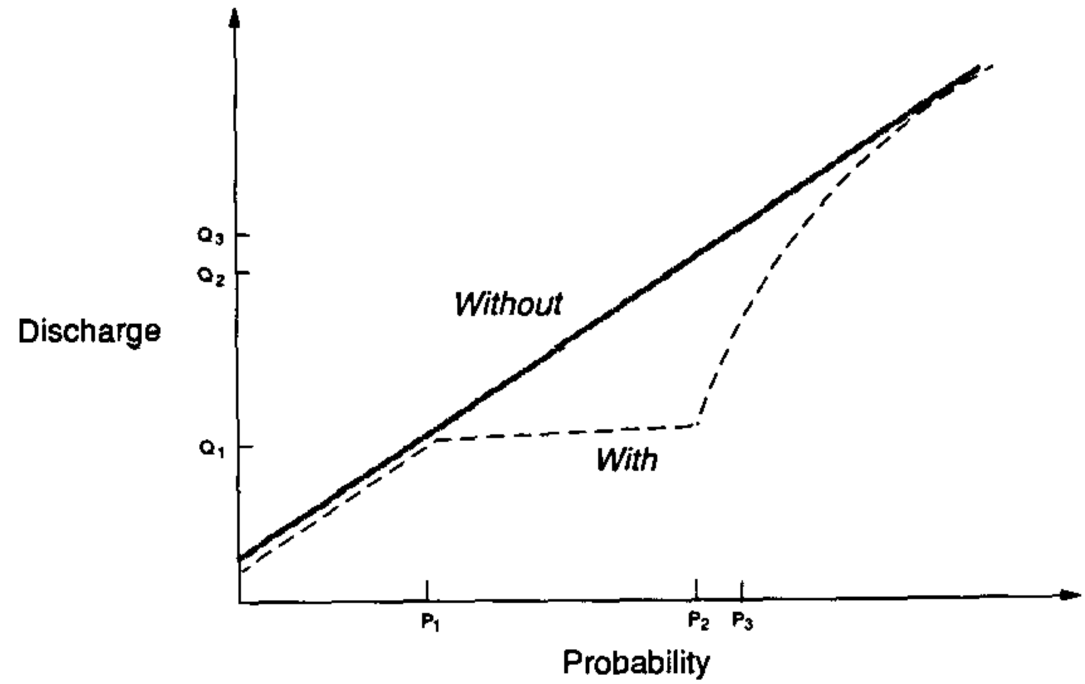

Figure 4-4. Discharge-frequency function modifications due to reservoir

Table 4-2
Steps in Evaluating Proposed Storage Alternatives

1. Define a set of without-project inflow hydrographs. These should cover the range of likely events, including frequent small events, infrequent large events, major historical events, etc.

2. Identify a "target" for reliability analysis. This may be the channel capacity downstream, the flow corresponding to the maximum stage before damage is incurred, or any other target appropriate for a particular floodplain.

3. Select a trial reservoir location, capacity, and outlet configuration. Develop the elevation-area-discharge functions required for reservoir routing for this alternative.

4. For each inflow hydrograph, in turn, compute the corresponding outflow hydrograph.

5. Compute the flood damage corresponding to the hydrograph peak.

6. Compare the outflow peak to the target to determine if the regulated flow or stage exceeds the target.

7. Repeat steps 3-5 for the range of inflow events. Determine the expected flood damage and the overall reliability of the alternative, defined as the frequency of meeting the target.

8. Repeat steps 2-6 for all reservoir alternatives.

9. Compare the economic efficiency and the reliability of the alternatives to select a recommended plan.

(2) Hydrologic-engineering studies formulate operation rules for controlled reservoirs as a component of any plan that includes such a reservoir. EM 1110-2-3600 presents guidance on operation rule definition. Computer program HEC-5 (USACE 1982b), which is described in Appendix B, is designed for simulation of flood-control reservoir operation. Publications from HEC describe how the program can be used to find operation rules.

(3) ER 1110-8-2 (FR) requires consideration of the effects of absence of personnel to regulate a reservoir, misoperation, and interruptions in communications during extreme events. For proper comparison of alternative plans, this cannot be simply an acknowledgement that these events may occur. A qualitative assessment must be made. For example, the hydrologic engineering analysis should define the discharge reduction possible for various events if the operator is making release decisions without knowledge of other than the reservoir pool elevation and the rate of pool rise.

c. Other considerations. To ensure proper performance of reservoirs for flood-damage reduction, the hydrologic engineer must consider also the following:

(1) Impact of debris/trash. A complete plan must include features that will minimize adverse impacts of outlet plugging due to debris.

(2) Safety features. A complete plan must include features to protect public safety at the reservoir site, particularly when the project is operating at capacity.

(3) Sedimentation. Chapter 5 of EM 1110-2-4000 provides a detailed description of sedimentation problems due to reservoirs, including those shown in Table 4-3. That EM also points out that “Eventually, all reservoirs will fill with sediment.” The hydrologic engineer must conduct a sedimentation study to identify the problems and should include remedial features if necessary.

4-6. Dam Safety Evaluation

The discharge-reduction benefit of a reservoir is accompanied by the hazard of dam failure. Corps policy, as stated in ER 1110-8-2 (FR), is that “... a dam failure must not present a hazard to human life ...” Accordingly, any reservoir plan must be formulated to comply with this safety requirement, and the impact of catastrophic failure of any proposed reservoir plan must be evaluated to confirm that this performance constraint is satisfied.

Table 4-3
Impact of Reservoir on Stream-System Morphology (from EM 1110-2-4000)

1. Rise in base level, and associated aggradation, of the main stem upstream from the dam due to the reservoir impoundment;

2. Fall in base level of the main stem downstream from the dam due to modified hydrographs;

3. Fall in base level of the main stem downstream from the dam due to degradation of the channel bed;

4. Changes in downstream channel capacity.

a. Formulation to minimize catastrophic consequences when capacity is exceeded. ER 1110-8-2 (FR) identifies four design standards, depending on the type of dam and risk to life. Table 4-4 describes these. The hydrologic engineering study should determine the standard appropriate for plan formulation and ensure that the standard is used for all project features.

b. Failure evaluation. The impact of dam failure can be estimated with hydraulics models described in EM 1110-2-1416 or with the routing models of EM 1110-2-1417. Three aspects of dam failure must be considered by the hydrologic engineer: (1) formation of a breach, an opening in the dam as it fails; (2) flow of water through this breach; and (3) flow in the downstream channel. However, the operating characteristics of the reservoir change with time as the breach grows. For convenience in analysis, a breach commonly is assumed to be triangular, rectangular, or trapezoidal, and to enlarge at a linear rate. At each instant that the breach dimensions are known, the flow of water through the breach can be determined with principles of hydraulics. Subsequent movement of the outflow hydrograph through the downstream channel is modeled with one of the routing models.

4-7. Environmental Impacts

a. Construction of a reservoir can have significant environmental and social impacts, and information provided can be critical in evaluation of these impacts. Table 4-5 illustrates this; the list is by no means all-inclusive.

b. One particular serious environmental issue is preservation of wetlands. 40 CFR 230.41(a)(1) defines wetlands as “... those areas that are inundated or saturated

Table 4-4
Design Standards for Dam Safety

Standard	Application
1	Applies to dams located such that human life is at risk. In that case, the dam must be designed to pass safely a flood event caused by the probable maximum precipitation (PMP) occurring over the catchment upstream of the reservoir. PMP is a "... quantity of precipitation that is close to the physical upper limit for a given duration over a particular basin (WMO 1983)." Corps studies will use PMP amounts developed by the Hydrometeorological Section of the National Weather Service. Runoff from the PMP is computed using models and procedures described in EM 1110-2-1417 and EM 1110-2-1411.
2	Applies to dams "where relatively small differentials between headwater and tailwater elevations prevail during major floods." These structures must be able to pass safely major floods typical of the region, without incurring excessive damage downstream and without sustaining damage that would render the dam inoperable.
3	Applies to dams "where failure would not jeopardize human life nor create damage beyond the capabilities of the owner to recover." These structures should be planned so failure related to hydraulic capacity will result in no measurable increase in population at risk and in a negligible increase in property damage over nonfailure damage.
4	Applies to small recreational and agricultural water supply reservoirs. The design in this case is "... usually based on rainfall-runoff probability analysis and may represent events of fairly frequent occurrence." The decision likely will be based on economic considerations: Does the cost of a more reliable structure exceed the expected cost of repair or replacement?

Table 4-5
Hydrologic Engineering Information Required to Assess Environmental Impacts

Potential Impact	Hydrologic Engineering Information Required to Assess Impact
Loss of wildlife habitat due to ponding	Inundation due to and duration of ponding
Loss of vegetation in ponded area	Inundation due to and duration of ponding
Inundation of archeological sites	Extent of and depth of inundation
Increased in-stream temperature, increased turbidity, reduced dissolved oxygen downstream of reservoir	With-plan discharge-frequency, results of water quality simulation.
Improved recreational opportunities due to pond	Pond stage-frequency
Loss of downstream stream recreation due to reduced discharge	Discharge-frequency, stage-frequency

by surface or groundwater at a frequency and duration sufficient to support, and that under normal circumstances do support, a prevalence of vegetation typically adapted for life in saturated soil conditions (ASCE/WEF 1992)."

The hydrologic engineering study done in cooperation with environmental elements must identify any such areas to permit protection as required under Section 404 of the Federal Water Pollution Control Act.